

CALIFORNIA POLYTECHNIC STATE UNIV.

## Design and Evaluation of Thrust Vectored Nozzles Using a Multicomponent Thrust Stand

Final Progress Report 10/01/88 - 01/31/90

NASA-Ames Grant Number NAG 2-559

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THRUST VECTORED NOZZLES USING A  
MULTICOMPONENT THRUST STAND Final Progress  
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COLOR ILLUSTRATIONS**

**CALIFORNIA POLYTECHNIC STATE UNIVERSITY  
San Luis Obispo, California 93407**

**Design and Evaluation of Thrust Vectored Nozzles  
Using a Multicomponent Thrust Stand**

**Final Progress Report 10/01/88 - 01/31/90**

**NASA-Ames Grant Number NAG 2-559**

**Thomas W. Carpenter, Principal Investigator & Professor, Mechanical Engineering**

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## INTRODUCTION

Future aircraft with the capability of short takeoff and landing, and improved maneuverability especially in the post-stall flight regime will incorporate exhaust nozzles which can be thrust vectored.

In order to conduct thrust vector research in the Mechanical Engineering Department at Cal Poly, a program was planned with two objectives; 1) Design and construct a multicomponent thrust stand for the specific purpose of measuring nozzle thrust vectors; and 2) to provide quality low moisture air to the thrust stand for cold flow nozzle tests.

Professor Thomas W. Carpenter and Ernest W. Blattner have been assigned project objectives 1 and 2, respectively. Robert Stagner provided an extensive review of literature on multicomponent thrust stands. From this review it was concluded that an accurate thrust stand of the orthogonal tripod geometry could be designed and fabricated (Ref. 1). Juanita Contreras provided detailed drawings of the stand, Appendix 1, and additional stress analysis of load cell supports. The multi-component thrust stand was then fabricated from stainless steel, Figure 1. Additional preliminary designs for thrust nozzles were also completed by Greg McIntosh and these can be reviewed in Appendix 2. This completed objective 1. For objective 2, Dennis Lencioni analyzed the air supply system from tank to test stand and provided theoretical pressure losses. In addition, he reviewed the capabilities of the fluke data acquisition system and the software package PROGEN. Blowdown tests of the air supply system were performed which included water injection tests to provide flow visualization of the exit air flow from the nozzles, Figure 2.

### OBJECTIVE 1: Design and construct a multicomponent thrust stand.

The design constraints for the multicomponent thrust stand were approximately 100#f in the axial direction and approximately 20#f for side loads.

A review of literature was performed with regards to multicomponent thrust stands (Ref. 1). From this review, a survey for multi-axis thrust measurements (Ref. 2) was located. From the research review it was noted that the most significant research related to thrust vectored stands was performed by Postma (Ref. 3 and 4). Not only did Postma review the feasibility of vector thrust load cells, but he provided a design for a nominal axial thrust capacity of 5000#f and a side thrust capacity of 1000#f (Ref. 3). Postma then provided a scaled down model with an axial load of 200#f and a side load of 40#f (Ref. 4). Postma's original thrust stand designating the orthogonal tripod geometry is shown in Figures 3, 4, and 5. Figure 3 provides the relative position of 6 load cells. Load cells L1, L2, and L3 measure the axial load, and cells L3, L4, and L5 provide side load measurement. Figures 4 and 5 provide x, y, z position coordinates for each load cell. For this design, each load cell was supported by two flexures. This was deemed necessary for the high loads (5000# axial, 1000# side) encountered.

The position coordinates for the reaction forces measured by the six load cells as shown by Figure 6 were:

<u>Reaction Force - #</u>	<u>Coordinate Position - Inches</u>	
$R_1$	$X_1 = 0$	$Y_1 = 5.0$
$R_2$	$X_2 = -4.33$	$Y_2 = -2.5$
$R_3$	$X_3 = 4.33$	$Y_3 = -2.5$
$R_4$	$X_4 = 0$	$Y_4 = 0$
$R_5$	$X_5 = -4.0$	
$R_6$	$X_6 = 4.0$	

Assuming a statically determinate structure, the force and moment component equations (6 components) were derived from the free body diagram of Figure 6 and are listed as:

$$F_Z = R_1 + R_2 + R_3$$

$$F_X = R_4$$

$$F_Y = -(R_5 + R_6)$$

$$M_Z = R_5 X_5 - R_6 X_6$$

$$M_X = R_1 Y_1 - R_2 Y_2 - R_3 Y_3$$

$$M_Y = R_2 X_2 - R_3 X_3$$

The moment equations apply the right hand rule about the corresponding axis.

Table 1, Reference 1, provides combined relation forces for an axial load of 5000#, side loads of 1000# in  $X$  and  $Y$  directions, moments of 12500 in-# about the  $X$  and  $Y$  axis, and a 2000 in-# moment about the  $Z$  axis.

The above 6-component thrust stand with its 12 flexures and high load capability exceeded our force needs by a factor of 50. However, Postma provided a scaled 25:1 model of the above thrust stand. This resulted in a model thrust stand with a nominal axial thrust capacity of 200#f and a side thrust capacity of 40#f. This, coincidentally, was exactly half of the proposed thrust of our design of 100#f and 20#f.

The scale model provided a redesign of the force links which replaced the expensive flexure supports of the large thrust stand with inexpensive small diameter pin supports. This scale model vector thrust stand is shown in Figure 7. For the scale model, the position coordinates were exactly halved to the given values.

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one signal conditioner option (-702). Once this option is received, the unit will be functional with regard to the load measurements of the thrust stand.

The system is capable of simultaneously monitoring force, temperature, voltage, current, and resistance through thirty independent channels at a rate of 1000 samples per second. The 1752A microprocessor is the link between the programmer and the 2400B data acquisition unit. Programs for data acquisition and control can be written with the aid of the available program development package called PROGEN. This software package consists of two disks, the programmer's disk and the operator's disk. The programmer's disk is used to set up system parameters, scan tasks, and reduce collected data. The operator's disk contains a compiled data acquisition program that is created by the programmer's disk using the system parameters, scan tasks, and data reduction algorithms specified by the programmer.

Scan tasks specify any or all of the thirty available channels to be monitored, the channel type, measurement type, and measurement parameters. The system can handle up to six scan tasks which are prioritized and begin with the name of the task such as: strain gage measurement, temperature measurement, etc.

PROGEN has the ability to manipulate data using a function command. Data is sent through any number of mathematical algorithms to produce output that is reduced as it is received. For example, function can simultaneously read nozzle pressure, temperature, and stagnation pressure, reduce this data and output mass flow rate, exit velocity, and mach number.

Once all programming has been completed, PROGEN will create a complete data acquisition program and copy it to the operator's disk. This program can then be run directly from the operator's disk.

A preliminary design of thrust vectored nozzles has been completed with drawings for plenum chambers 1 and 2 enclosed, Appendix 2. These nozzles are supplied by 2 inch diameter plenums and receive air through 1.50 inch diameter flex hoses. The plenums for each nozzle are offset for the purpose of allowing the placement of the nozzles on the thrust stand to be side-by-side with provision to separate the nozzles a distance of up to one or more diameters. This design will allow investigations of exit flow gas interactions with thrust vectored nozzles.

**OBJECTIVE 2:** Provide quality low moisture air to the thrust stand.

Initial blowdown tests of the air supply provided blowdown times of 40 seconds and supplied total pressures to the nozzles of 90 psia from a supply of 140 psia, (Ref. 1). This value of total pressure at the nozzle inlet appeared low and prompted a theoretical study of the head loss of the system. In Appendix 3 the total piping system and supply tank are shown. The piping system has been divided into 3 sections and sample head loss calculations have been calculated per each section. Table III provides theoretical head loss calculations for air for 12 different flow conditions. The results indicate a 10 to 35 psi pressure drop. The actual blowdown tests experienced pressure

losses 15 psi in excess of the predicted values. This indicates additional line losses but not significant enough to require correction at this time.

The moisture content of the air during blowdown tests appeared to be an acceptable low value. In this regard, blowdown tests were performed and water was added to the exit air stream to provide improved flow visualization of the exiting air. Figure 2 shows a blowdown test with dual water jets placed at the exit of the nozzle. A slight visual improvement of the flow stream was made. The photograph, however, leaves much to be desired before this technique will be useful in flow visualization.

### SUMMARY

The design and fabrication of the six-component thrust stand has been completed, Figure 1. Detailed evaluation tests of the thrust stand will continue upon the receipt of one signal conditioning option (-702) for the Fluke Data Acquisition System. Preliminary design of thrust nozzles with air supply plenums have been completed, Appendix 2. The air supply has been analyzed with regard to head loss, Table III. Initial flow visualization tests were conducted using dual water jets, Figure 2.

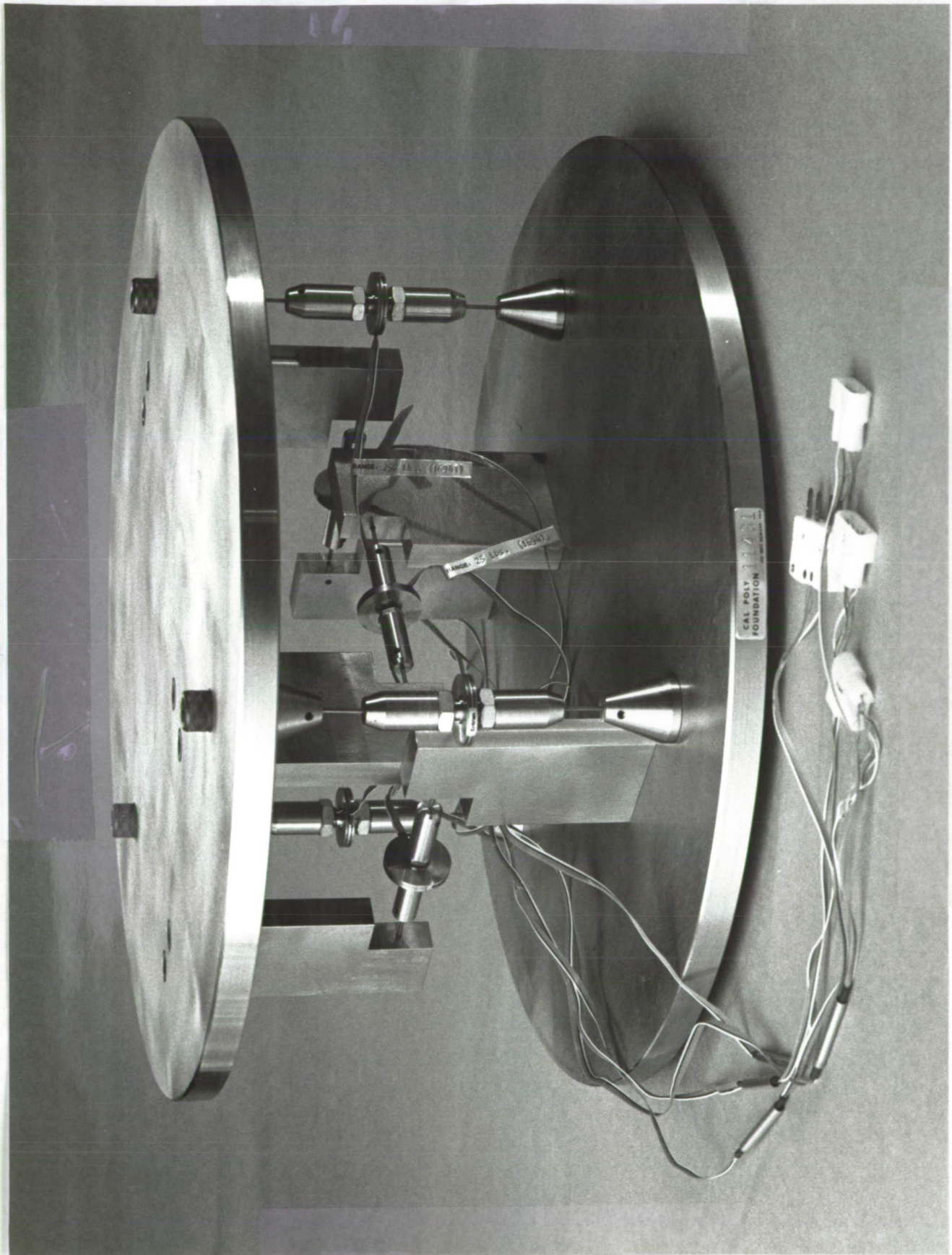


FIGURE 1. Assembled View of Multicomponent Thrust Stand

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**FIGURE 2. Flow Visualization Using Dual Waterjets**

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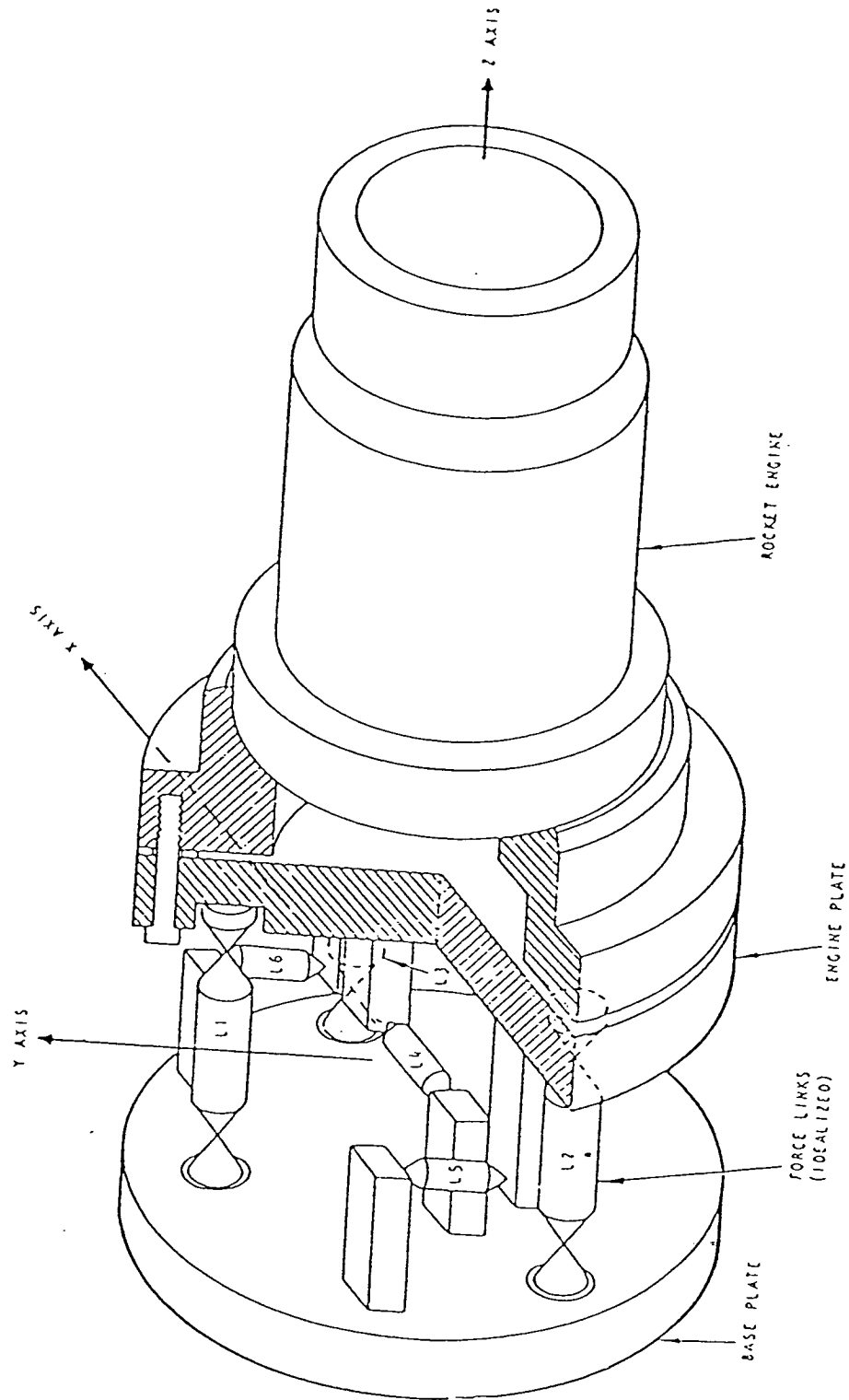


FIGURE 3. ORTHOGONAL TRIPOD GEOMETRY  
(Reference 3)





FORCES ARE POSITIVE IN THE DIRECTIONS OF THE ARROWS. MOMENTS ARE POSITIVE ACCORDING TO THE RIGHT HAND RULE. ALL FORCES ARE CONSIDERED TO BE APPLIED TO THE ENGINE SIDE OF THE BALANCE. FORCE LINK REACTION FORCES ARE CONSIDERED POSITIVE IN COMPRESSION.

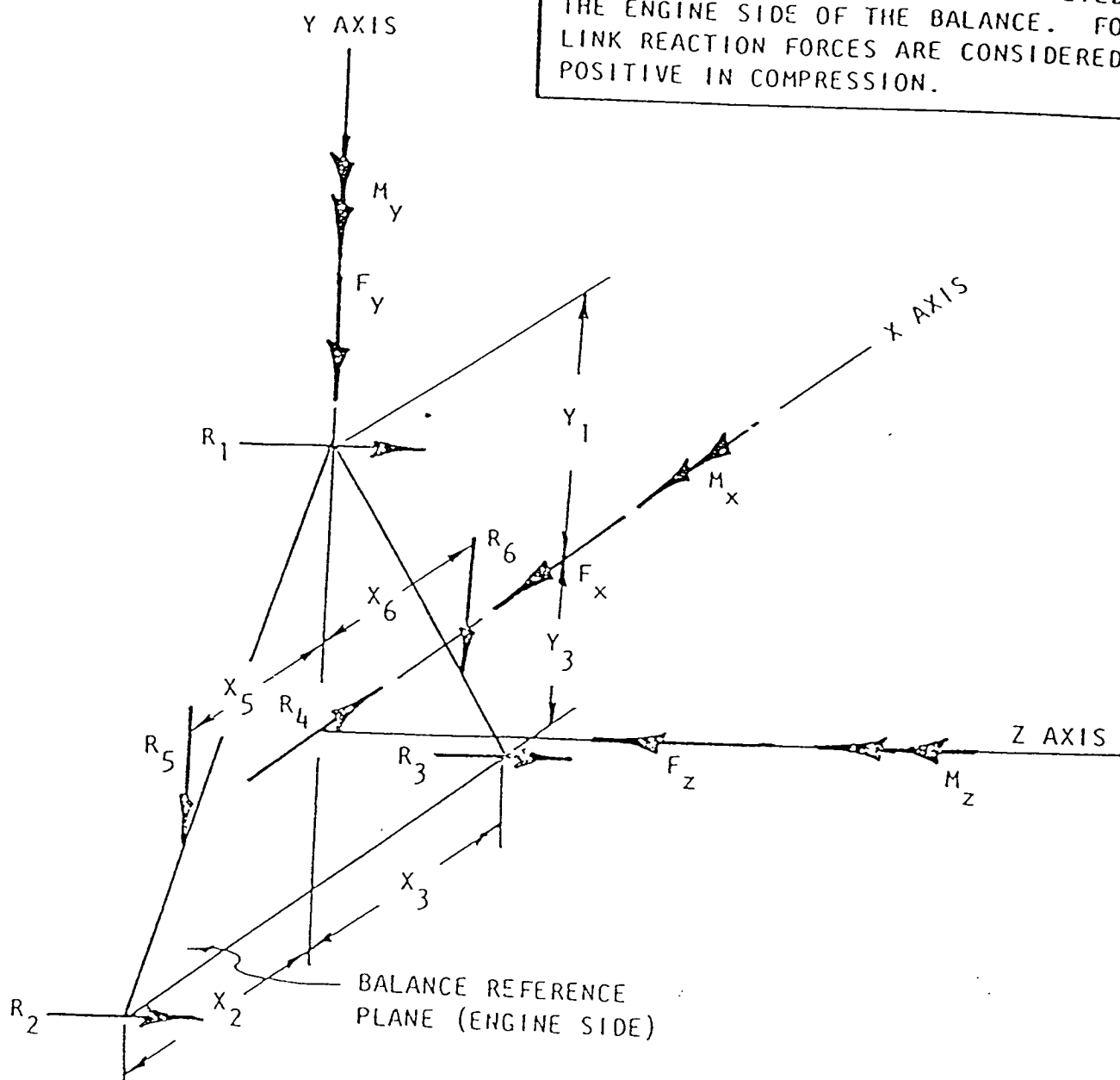


FIGURE 6. EXTERNAL FORCE AND MOMENT COMPONENTS AND FORCE LINK REACTION FORCES, ORTHOGONAL TRIPOD GEOMETRY (Reference 3)

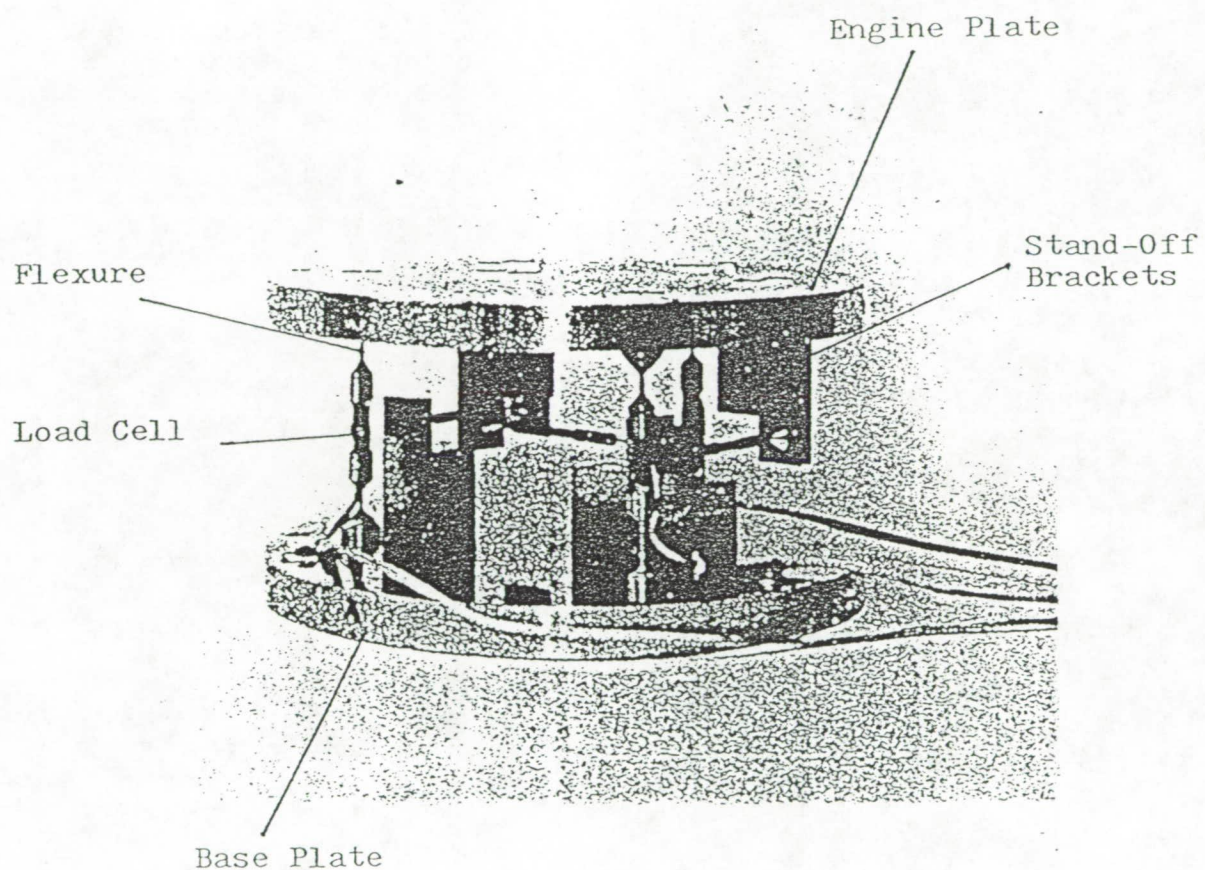


FIGURE 7. SCALE MODEL VECTOR THRUST LOAD CELL  
(Reference 4)

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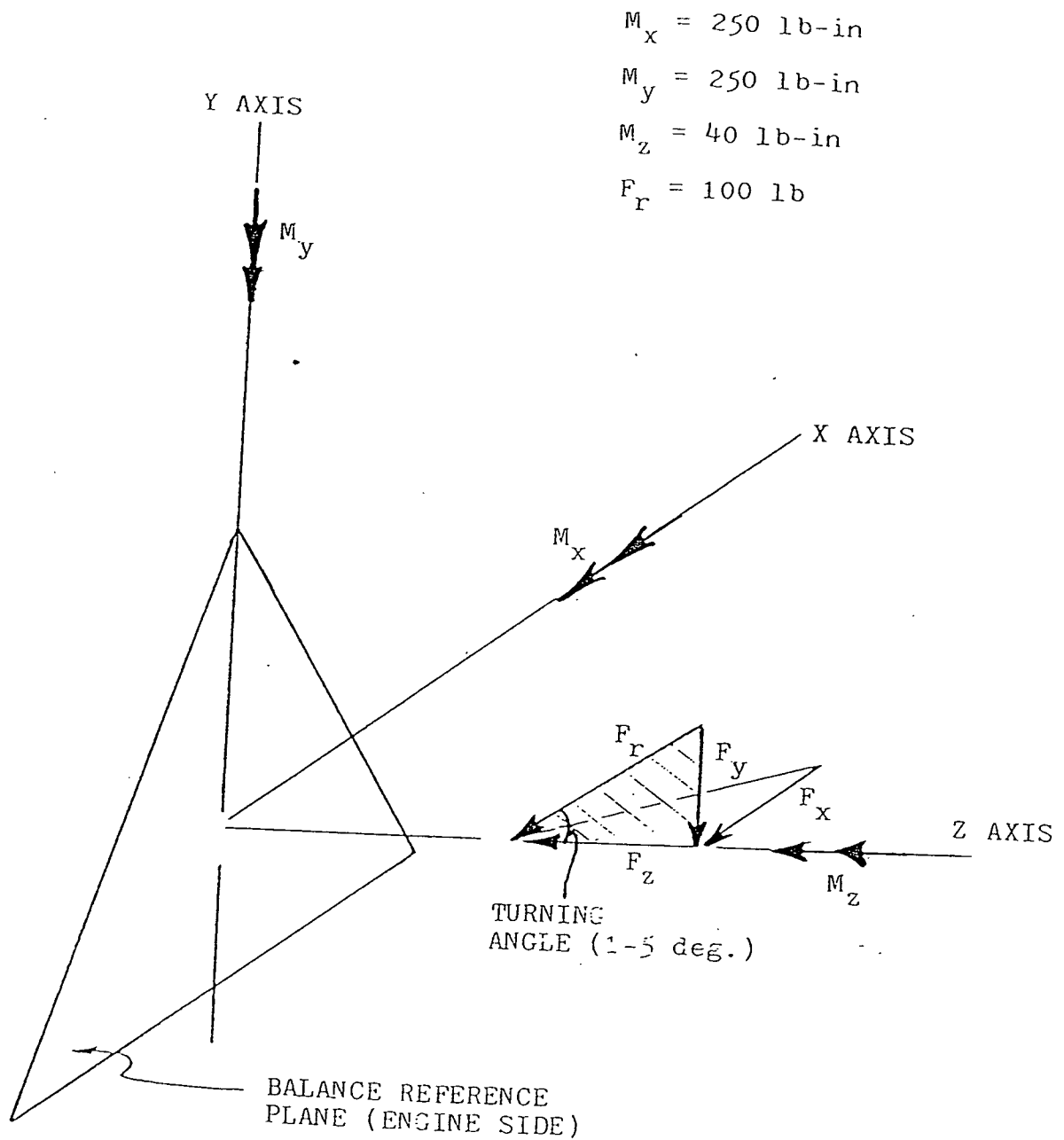


FIGURE 8. EXTERNAL FORCE (X-Z PLANE & Y-Z PLANE) WITH MOMENT COMPONENTS.

(Reference 1)

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1752 A

2452  
DATA  
ACQUISITION  
SYSTEM

2400B

FIGURE 9. Fluke 2452 Data Acquisition System



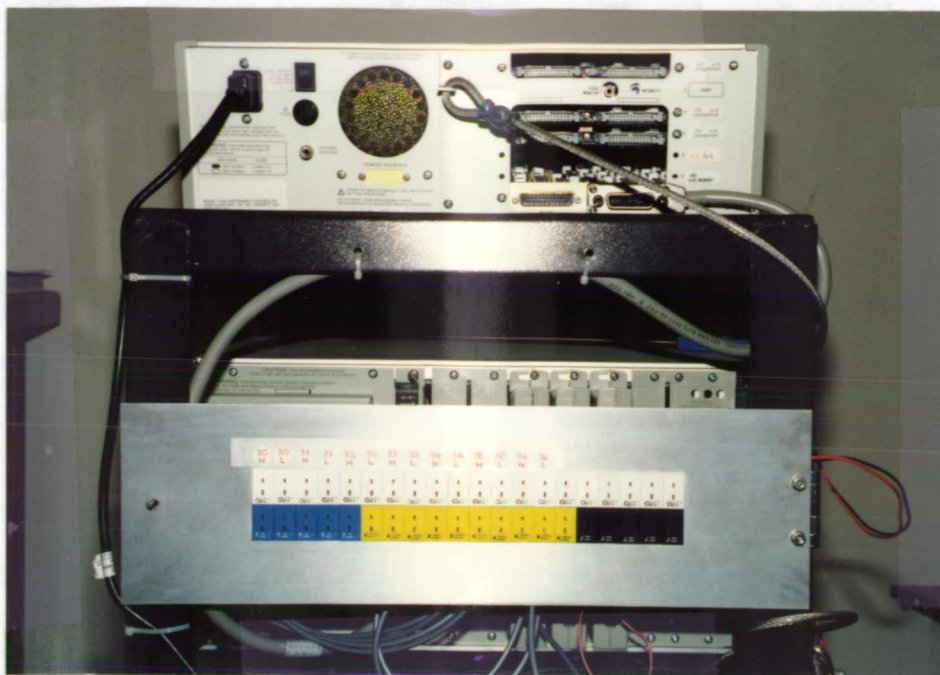


FIGURE 10. Fluke 2452 Data Acquisition

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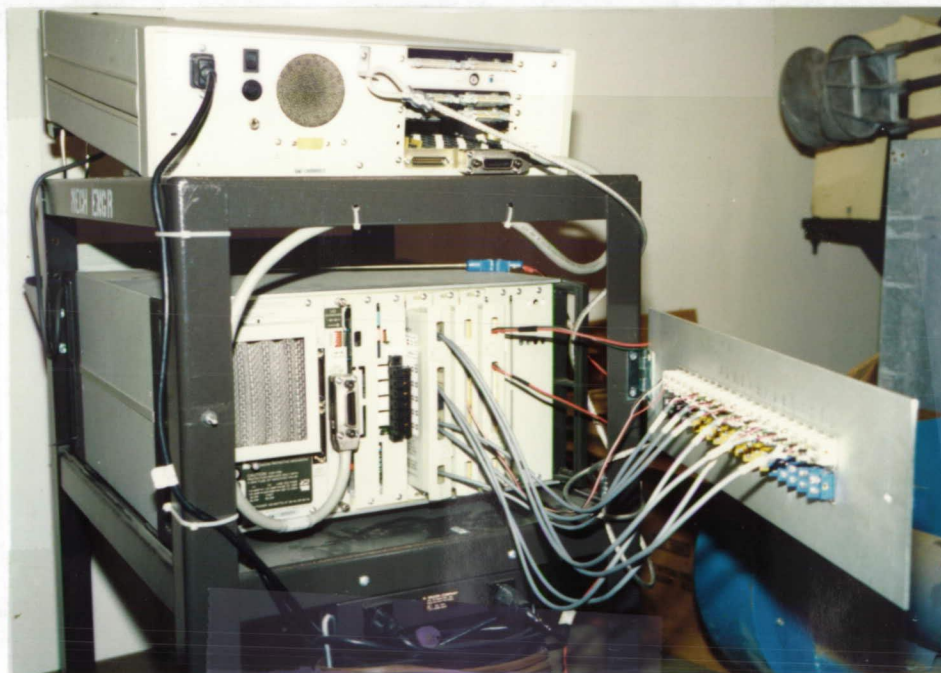


FIGURE 11. Fluke 2452 Data Acquisition System Indicating Input Side of 2400B Unit

	$F_z$ 5000 lb <sub>f</sub>	$F_x$ 1000 lb <sub>f</sub>	$F_y$ 1000 lb <sub>f</sub>	$M_y$ 12500 in-lb	$M_x$ 2000 in-lb	$M_z$ 2000 in-lb	$\Sigma R$ lb
R <sub>1</sub>	1666	---	---	---	1666	---	3333
R <sub>2</sub>	1666	---	---	1442	-833	---	2275
R <sub>3</sub>	1666	---	---	-1442	-833	---	-609
R <sub>4</sub>	---	1000	---	---	---	---	1000
R <sub>5</sub>	---	---	-500	---	---	250	-250
R <sub>6</sub>	---	---	-500	---	---	-250	-750

TABLE I. REACTION FORCES DUE TO EXTERNAL FORCE AND MOMENT COMPONENTS FOR THE FULL-SCALE VECTOR THRUST LOAD CELL (1:1 FORCE RATIO)

(Reference 1)



	$F_z$ 100 lb <sub>f</sub>	$F_x$ 20 lb <sub>f</sub>	$F_y$ 20 lb <sub>f</sub>	$M_y$ 250 in-lb	$M_x$ 40 in-lb	$M_z$ 40 in-lb	$\Sigma R_m$ lb
R <sub>1</sub>	33	---	---	---	67	---	100
R <sub>2</sub>	33	---	---	57.74	-33	---	57.74
R <sub>3</sub>	33	---	---	-57.74	-33	---	-57.74
R <sub>4</sub>	---	20	---	---	---	---	20
R <sub>5</sub>	---	---	-10	---	---	-10	-20
R <sub>6</sub>	---	---	-10	---	---	10	0

TABLE II. REACTION FORCES DUE TO EXTERNAL FORCE AND  
MOMENT COMPONENTS FOR HALF-SCALE VECTOR  
THRUST LOAD CELL (50:1 FORCE RATIO).

(Reference 1)

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Trial #	Mass Flow Rate lbm/s	Tank Pressure psi	Temperature R	Smoothness Ratio e/D	Pressure Change psi	Exit Pressure psi
1	2.5	125	530	0.00002	4.82	120.18
2	2.5	100	530	0.00002	6.07	93.93
3	2.5	75	530	0.00002	8.22	66.78
4	2.5	50	530	0.00002	12.98	37.02
5	3.5	125	530	0.00002	9.27	115.73
6	3.5	100	530	0.00002	11.75	88.25
7	3.5	75	530	0.00002	16.20	58.8
8	3.5	50	530	0.00002	27.45	22.55
9	5	125	530	0.00002	18.86	106.14
10	5	100	530	0.00002	24.34	75.66
11	5	75	530	0.00002	35.23	39.77
12	5	50	530	0.00002	*****	*****

TABLE III. Head Loss Calculations for Air Supply

### CITED REFERENCES

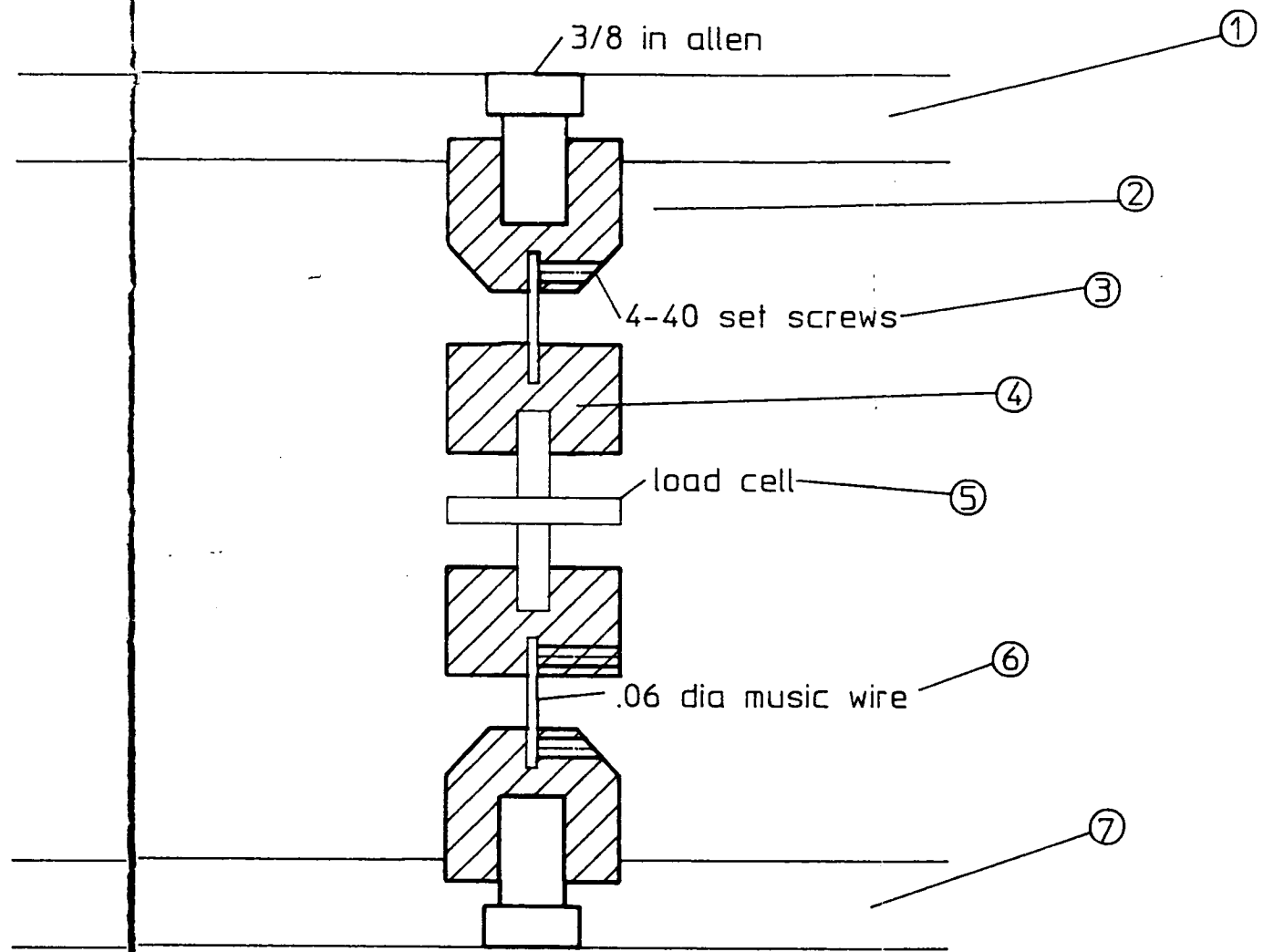
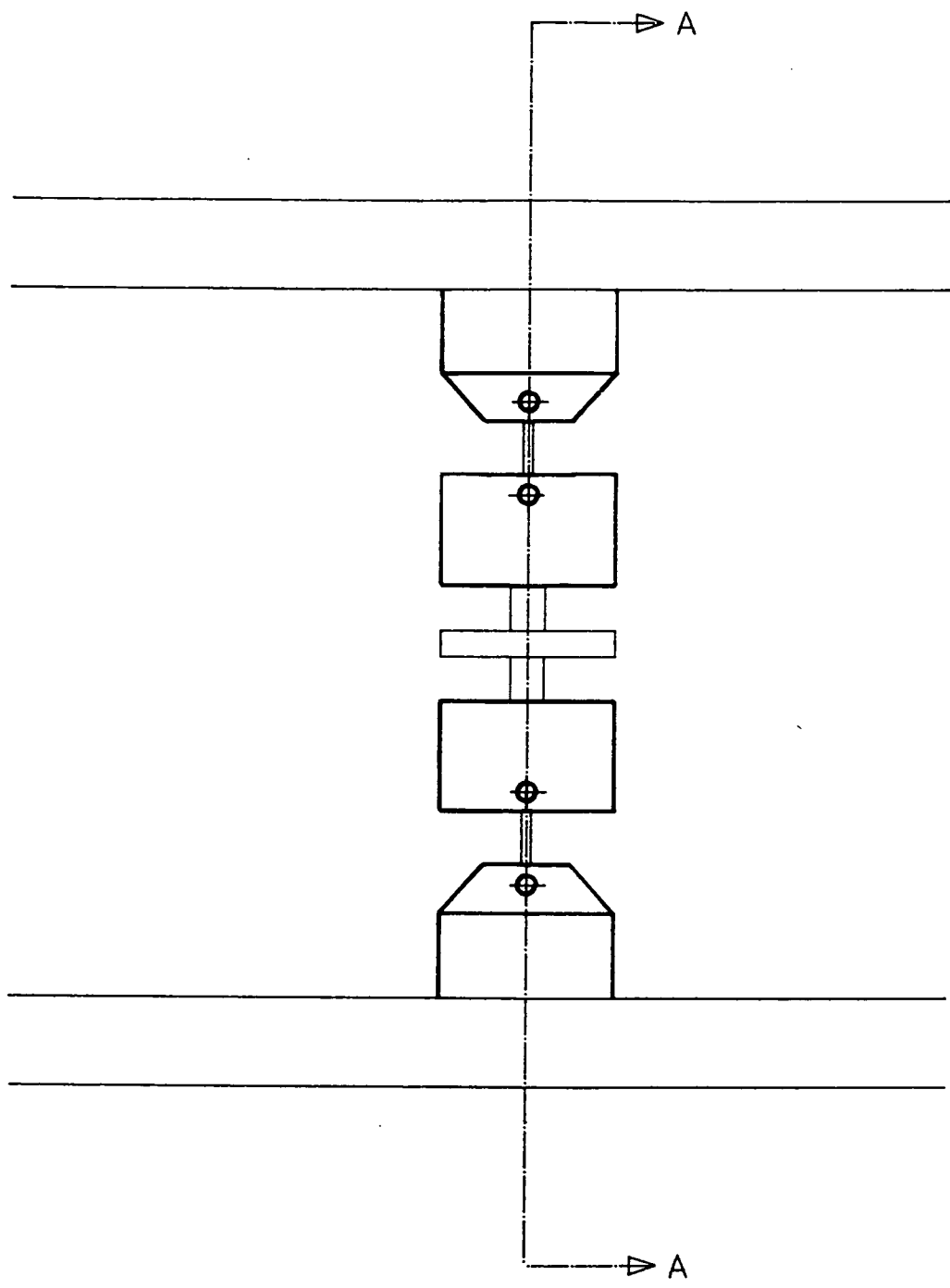
1. Carpenter, T.W., Blattner, E. W., Stagner, R. E., *"Design and Evaluation of Thrust Vecteded Nozzles Using a Multicomponent Thrust Stand."* Semi-annual progress report 10/01/88 - 05/01/89, NASA-Ames Grant Number NAG 2-559.
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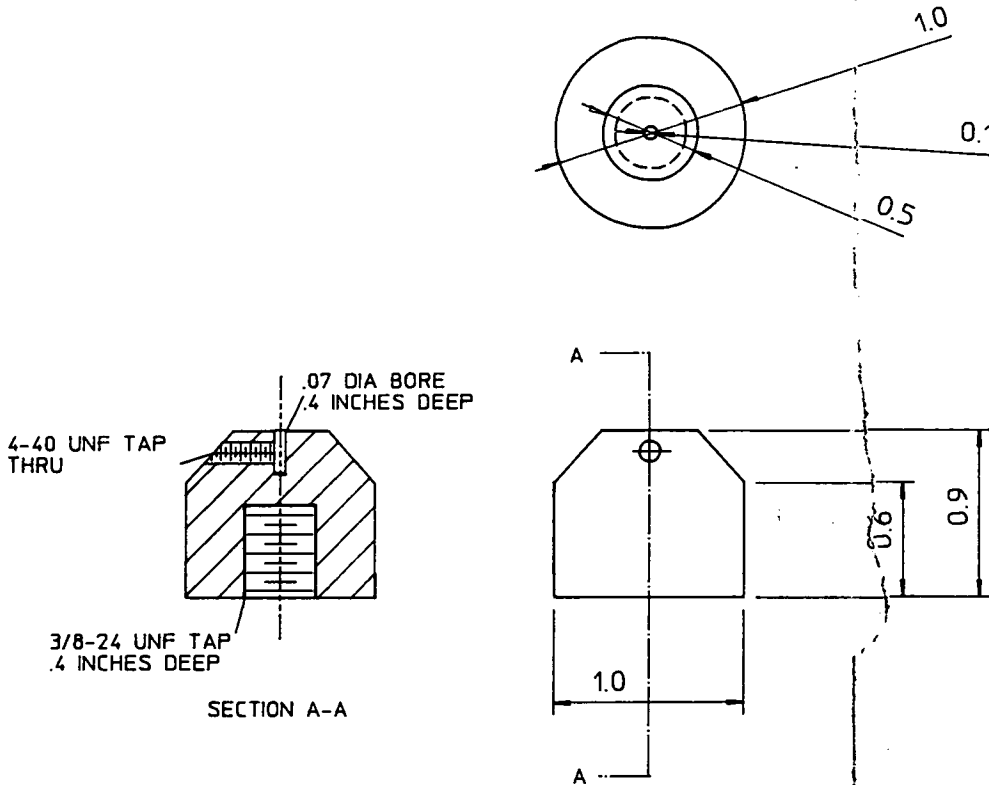
## **APPENDIX 1**

### **DETAILED DRAWING OF MULTICOMPONENT THRUST STAND**



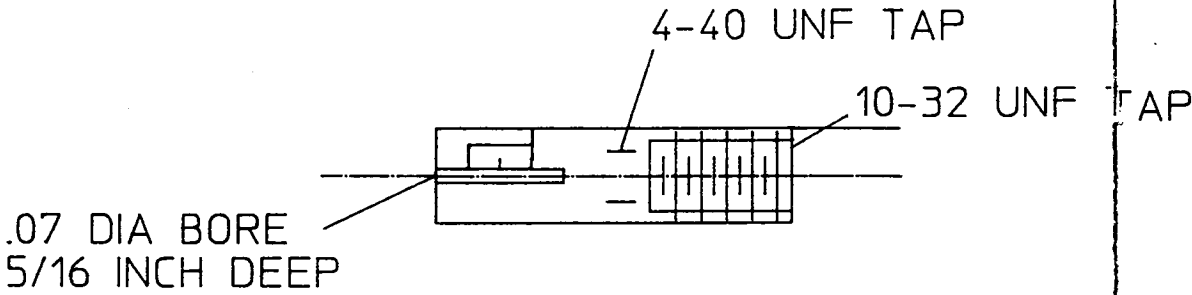
Section A-A

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		DRAWN BY: J. CONTRERAS		DATE: 11 NOVEMBER 1989

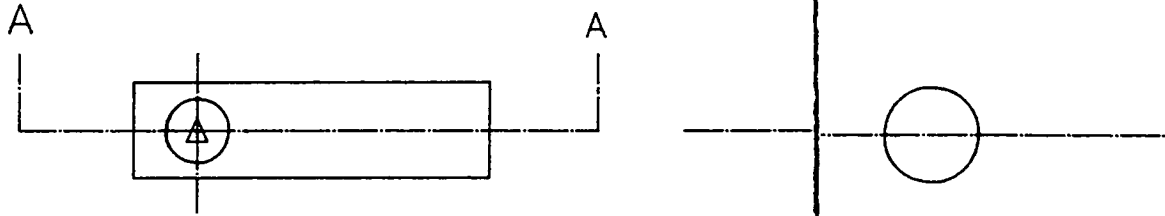


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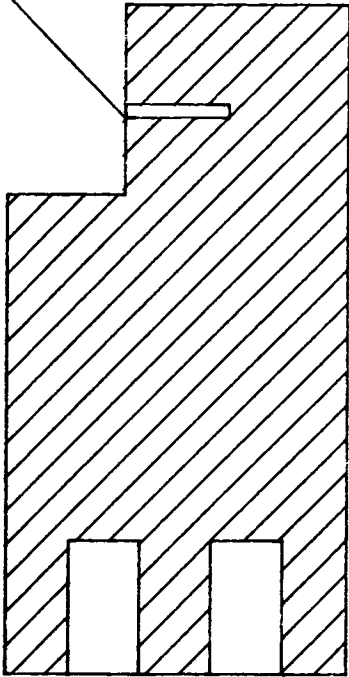


SECTION A-A

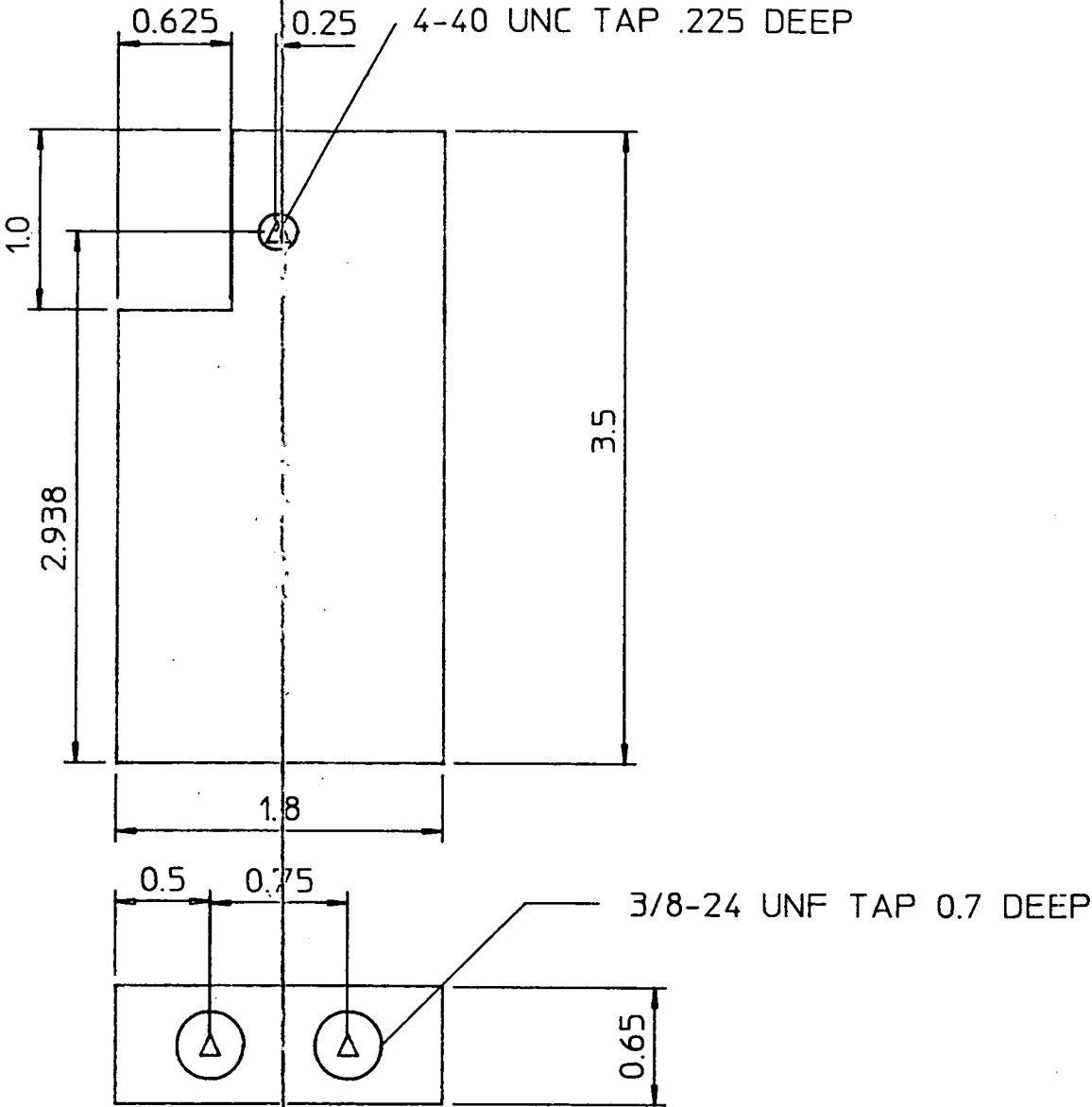


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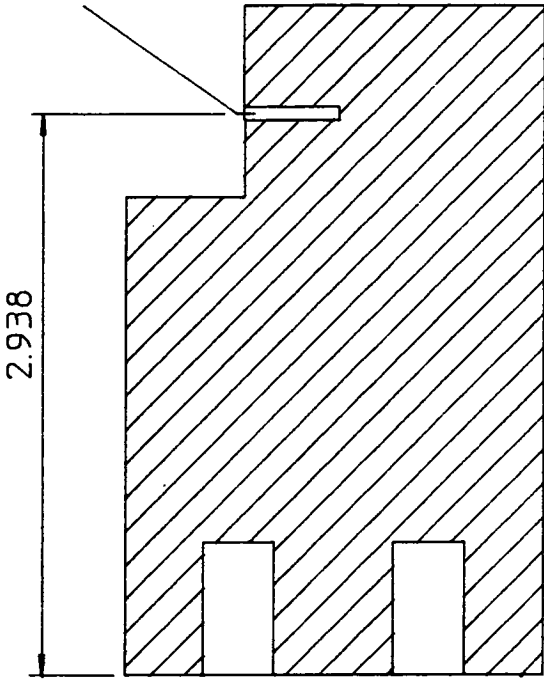


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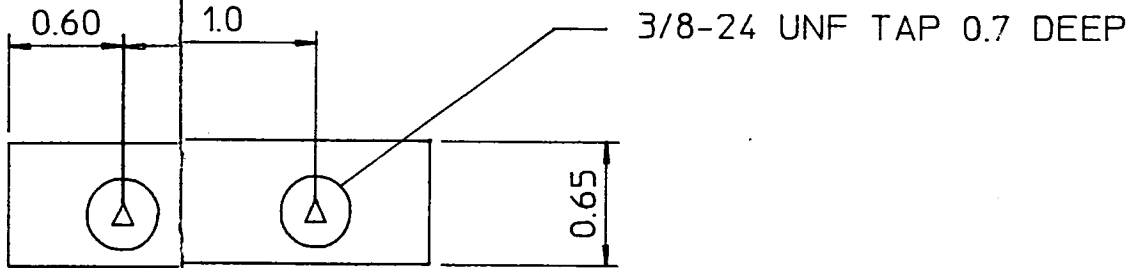
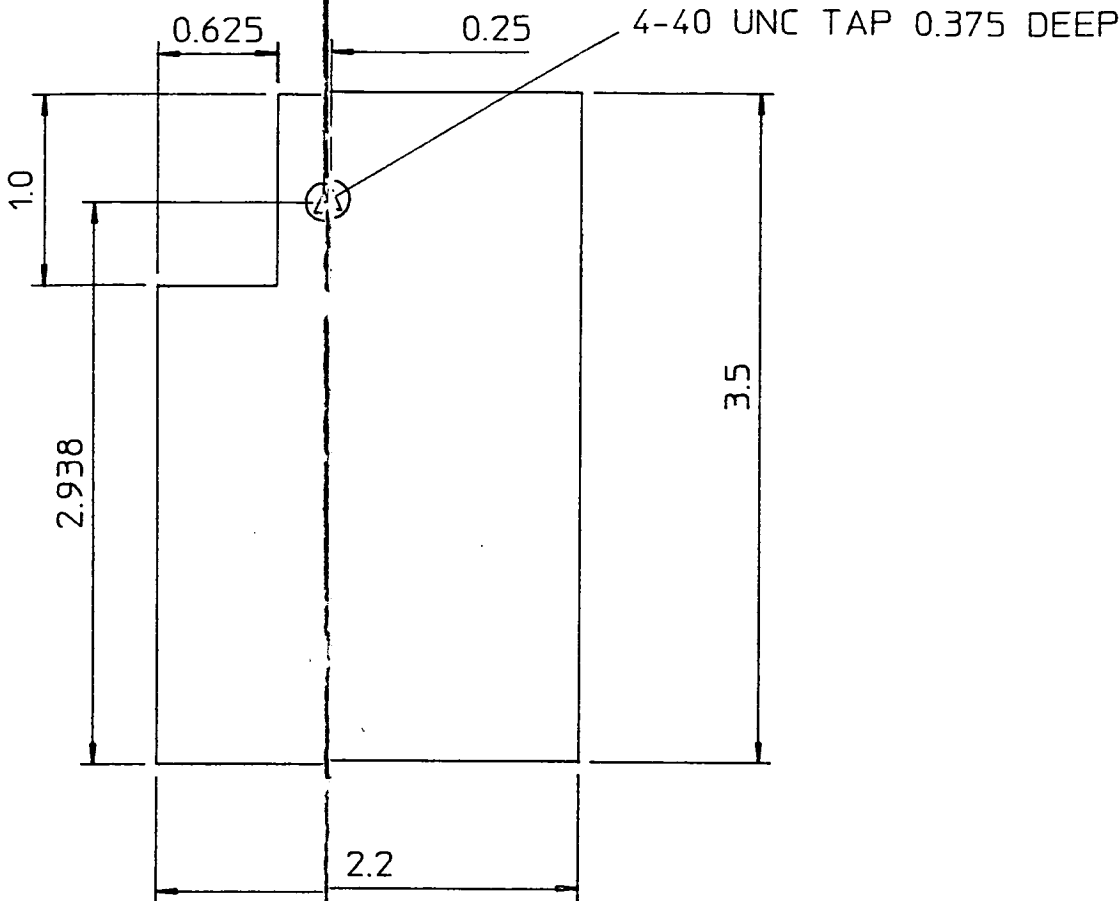


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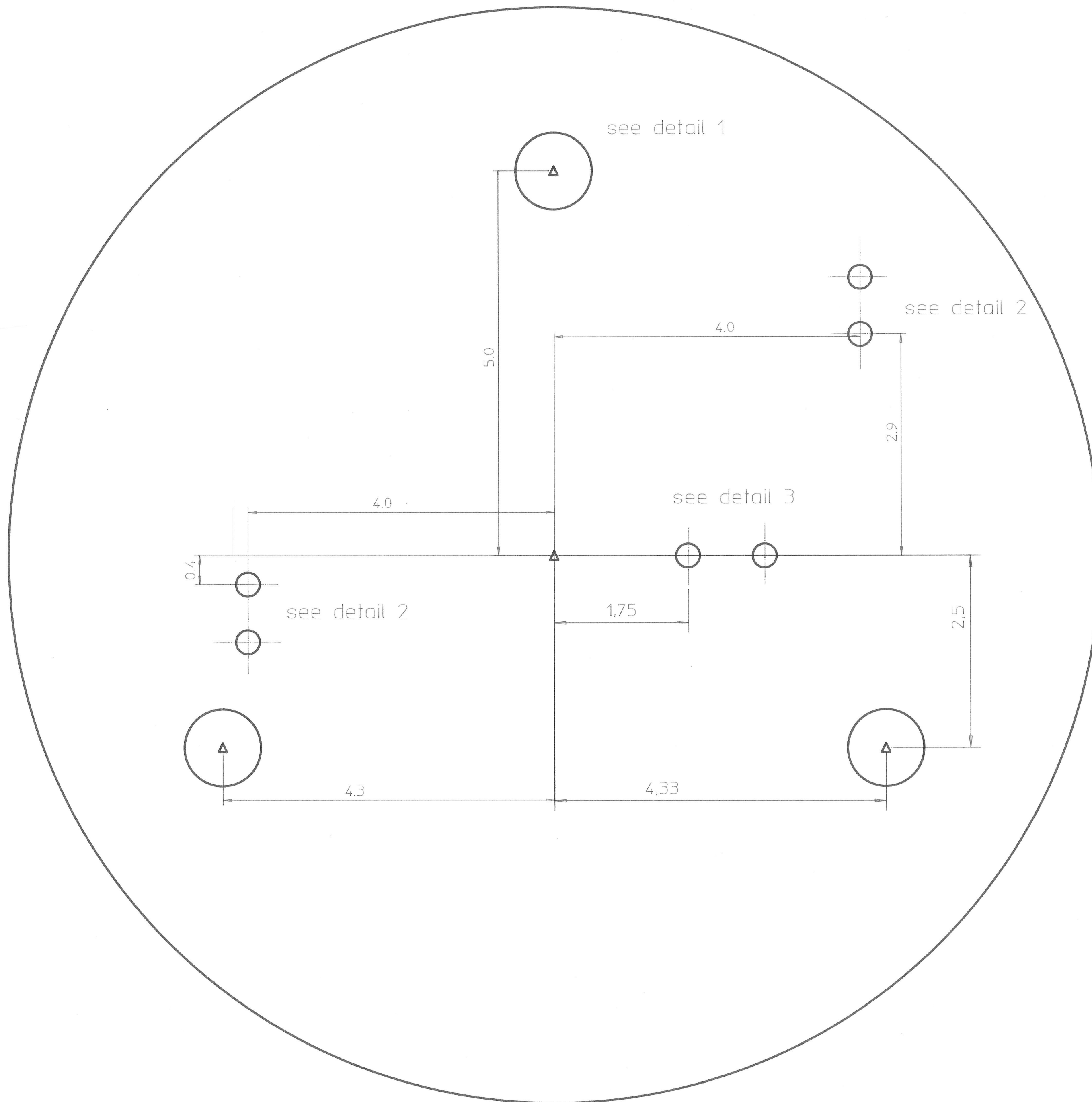
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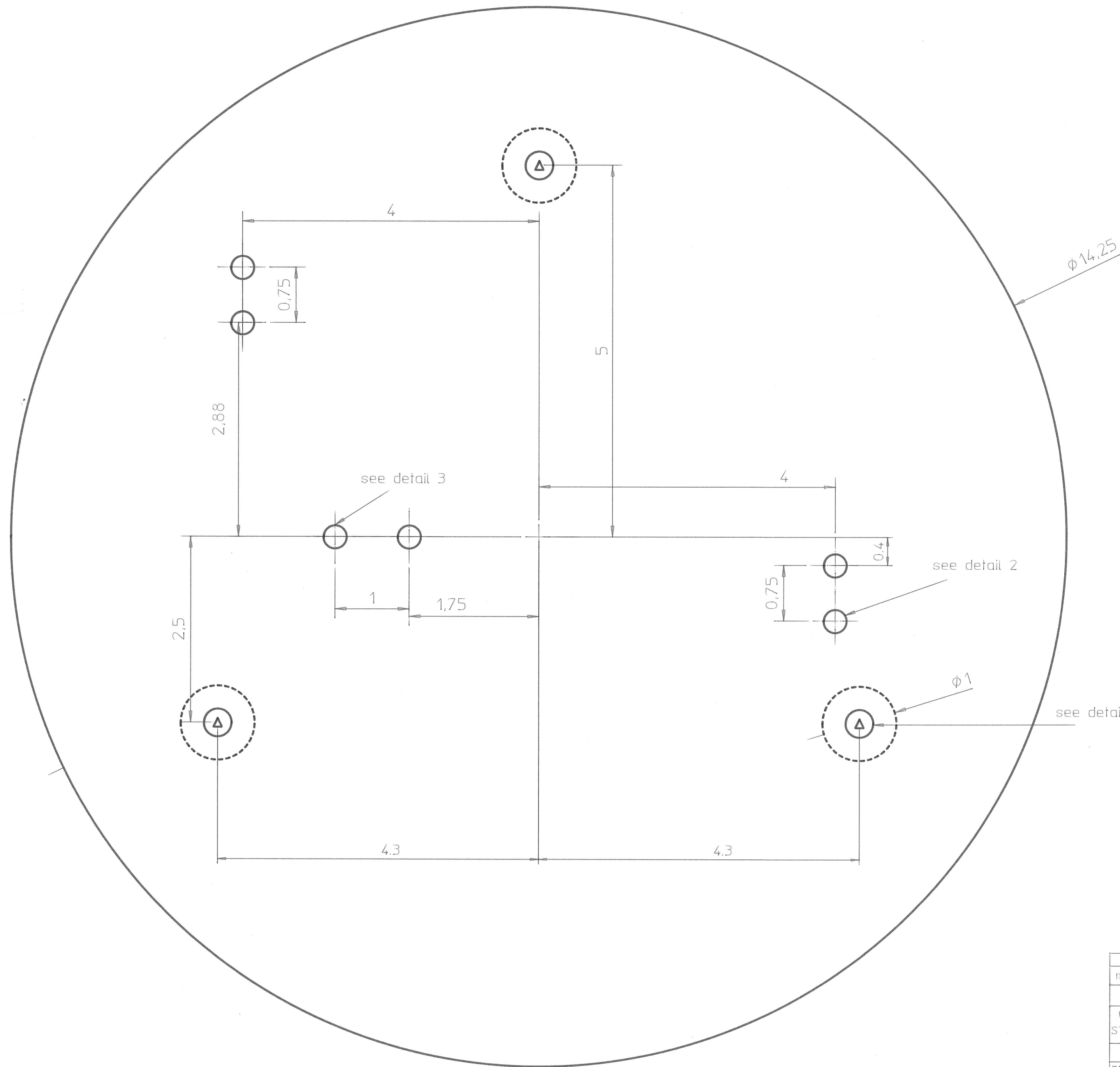
SECTION VIEW



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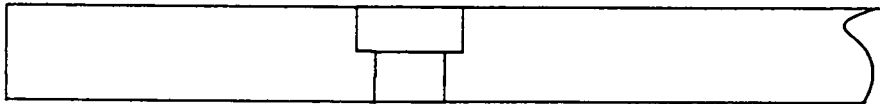
ITEM	QTY.	PART NO.	DESCRIPTION	SPECIFICATION
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TOLERANCES: .XX ± 0.01 .XXX ± 0.002		PAGE: OF DRAWN BY: J. CONTRERAS	REV. NO. DATE: 11 NOVEMBER 1989	



1	1	463-01	TOP PLATE	STAINLESS STEEL
ITEM	QTY.	PART NO.	DESCRIPTION	SPECIFICATION
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SCALE: 1:1 DIMENSIONS IN: IN			TEST STAND TOP PLATE	
TOLERANCES: .XX $\pm$ 0.01 .XXX $\pm$ 0.002			PAGE: OF DRAWN BY: J. CONTRERAS	REV. NO.: DATE: 18 NOVEMBER 1989

DETAIL 1  
3 places

3/8 dia bore  
counter bore 3/8 inch



DETAIL 3  
1 place

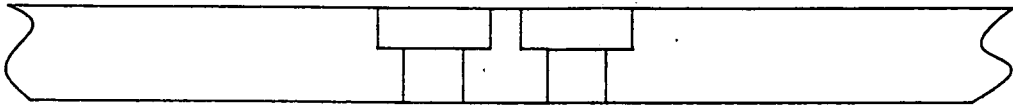
3/8 dia bores thru  
counter bore 3/8 inch



1 inch  
center to center

DETAIL 2  
2 places

3/8 dia bores thru  
counter bore 3/8 inch



.75 inch  
center to center

ITEM	QTY.	PART NO.	DESCRIPTION	SPECIFICATION
PARTS LIST				
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DIMENSIONS IN:		TOP & BOTTOM PLATE DETAILS		
TOLERANCES: .XX ± 0.01 .XXX ± 0.002				
		PAGE: OF		REV. NO.:
		DRAWN BY: J. CONTRERAS		DATE: 18 NOVEMBER 1989



## **APPENDIX 2**

### **PRELIMINARY DESIGN OF THRUST NOZZLES**

#### **PLENUM CHAMBER NO. 1**

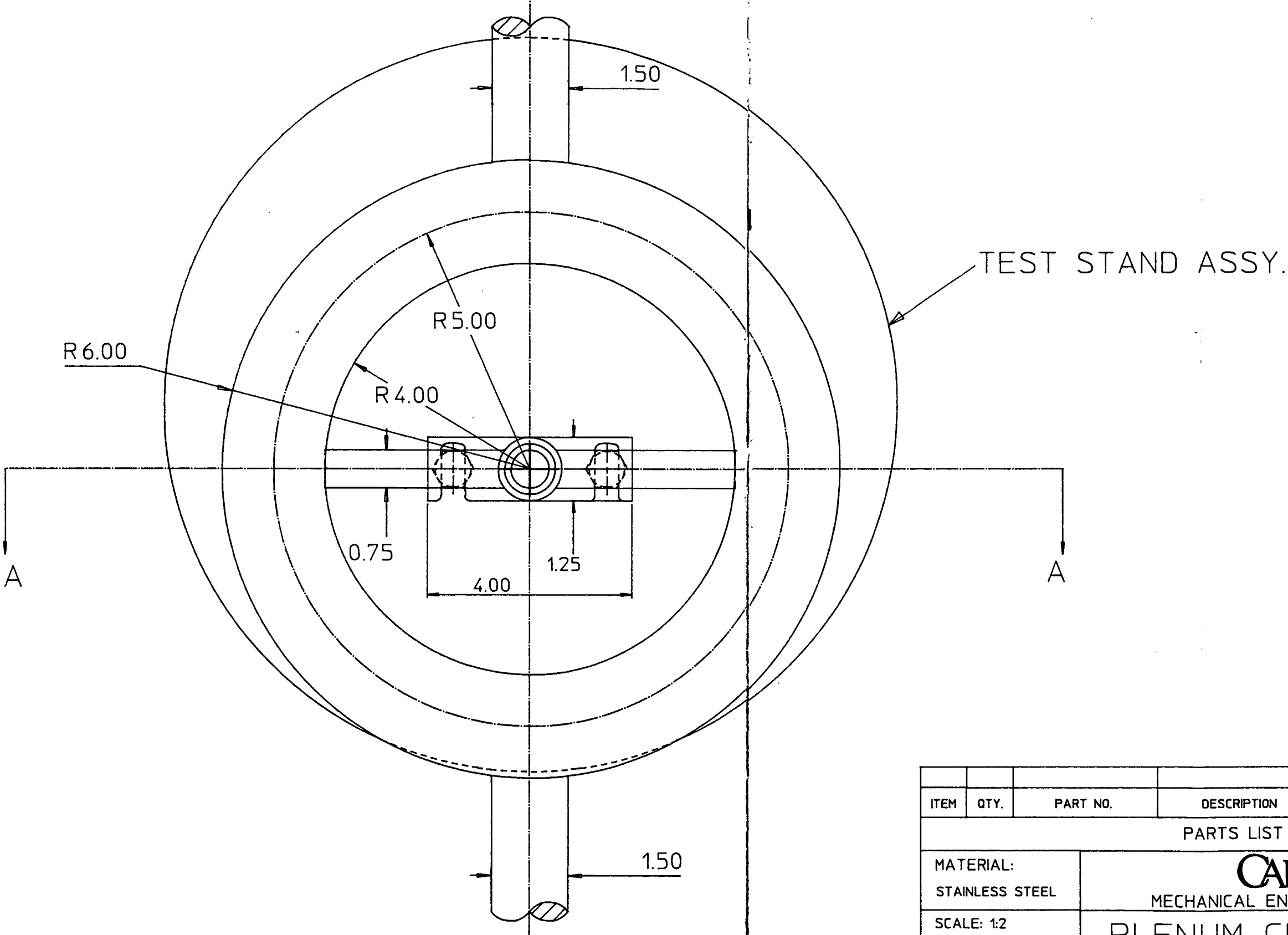
**TOP VIEW**

**SIDE VIEW**

#### **PLENUM CHAMBER NO. 2**

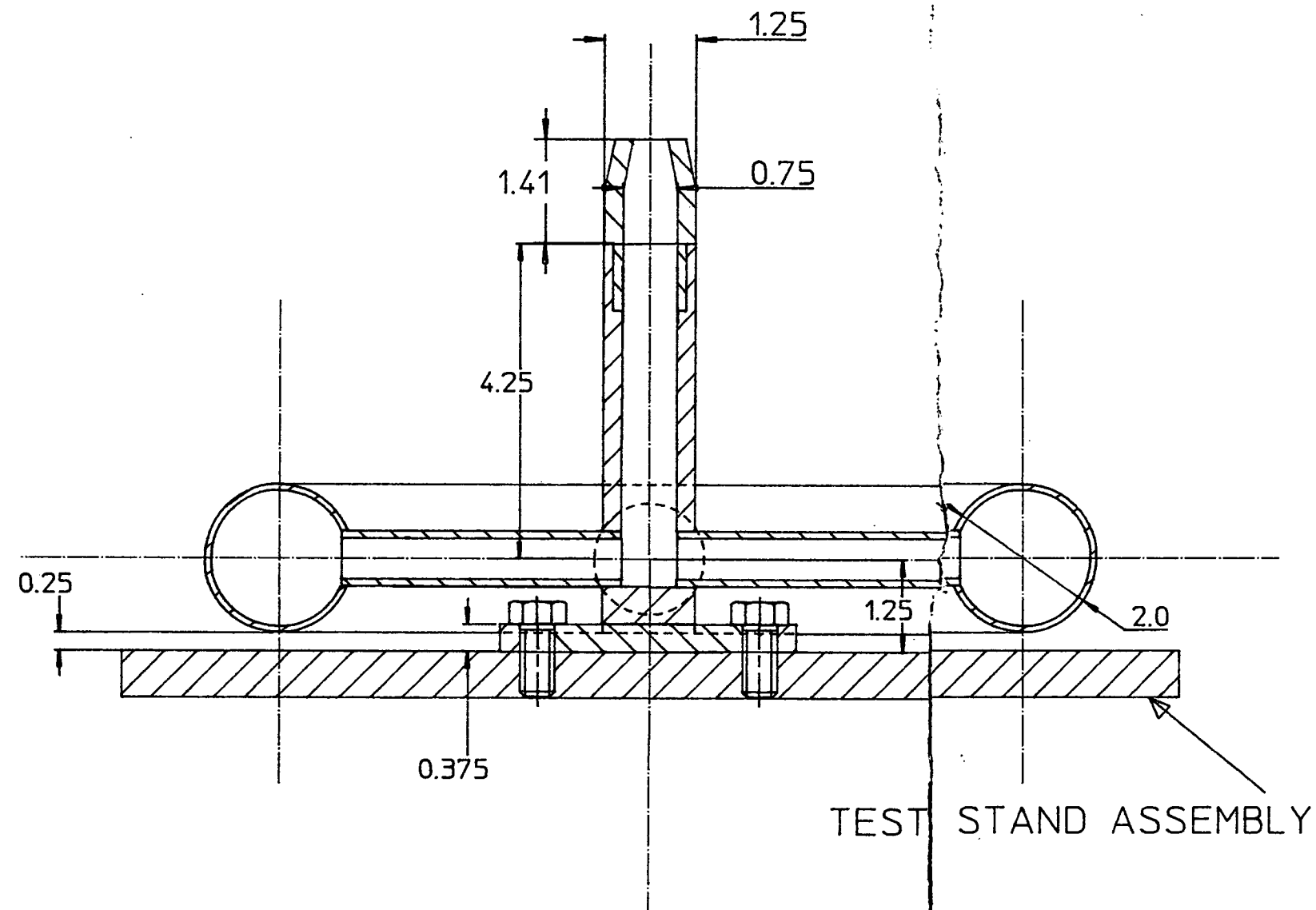
**TOP VIEW**

**SIDE VIEW**



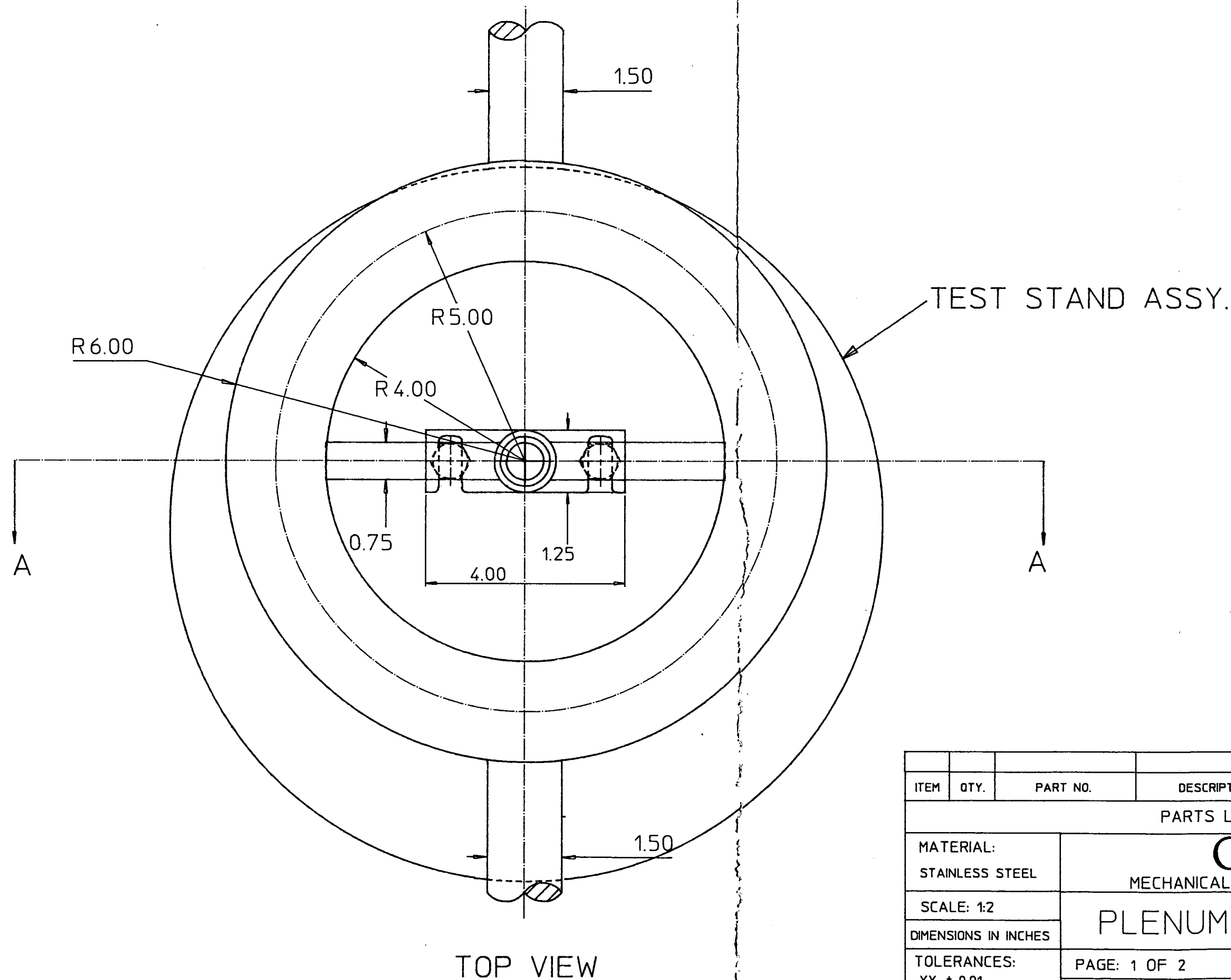
TOP VIEW

ITEM	QTY.	PART NO.	DESCRIPTION	SPECIFICATION	
PARTS LIST					
MATERIAL: STAINLESS STEEL		CAL POLY MECHANICAL ENGINEERING DEPARTMENT PLENUM CHAMBER No.1			
SCALE: 1:2					
DIMENSIONS IN INCHES					
TOLERANCES: .XX ± 0.01 .XXX ± 0.002		PAGE: 1 OF 2		REV. NO.:	
		DRAWN BY: G.C. MCINTOSH		DATE: 12 JANUARY 1990	

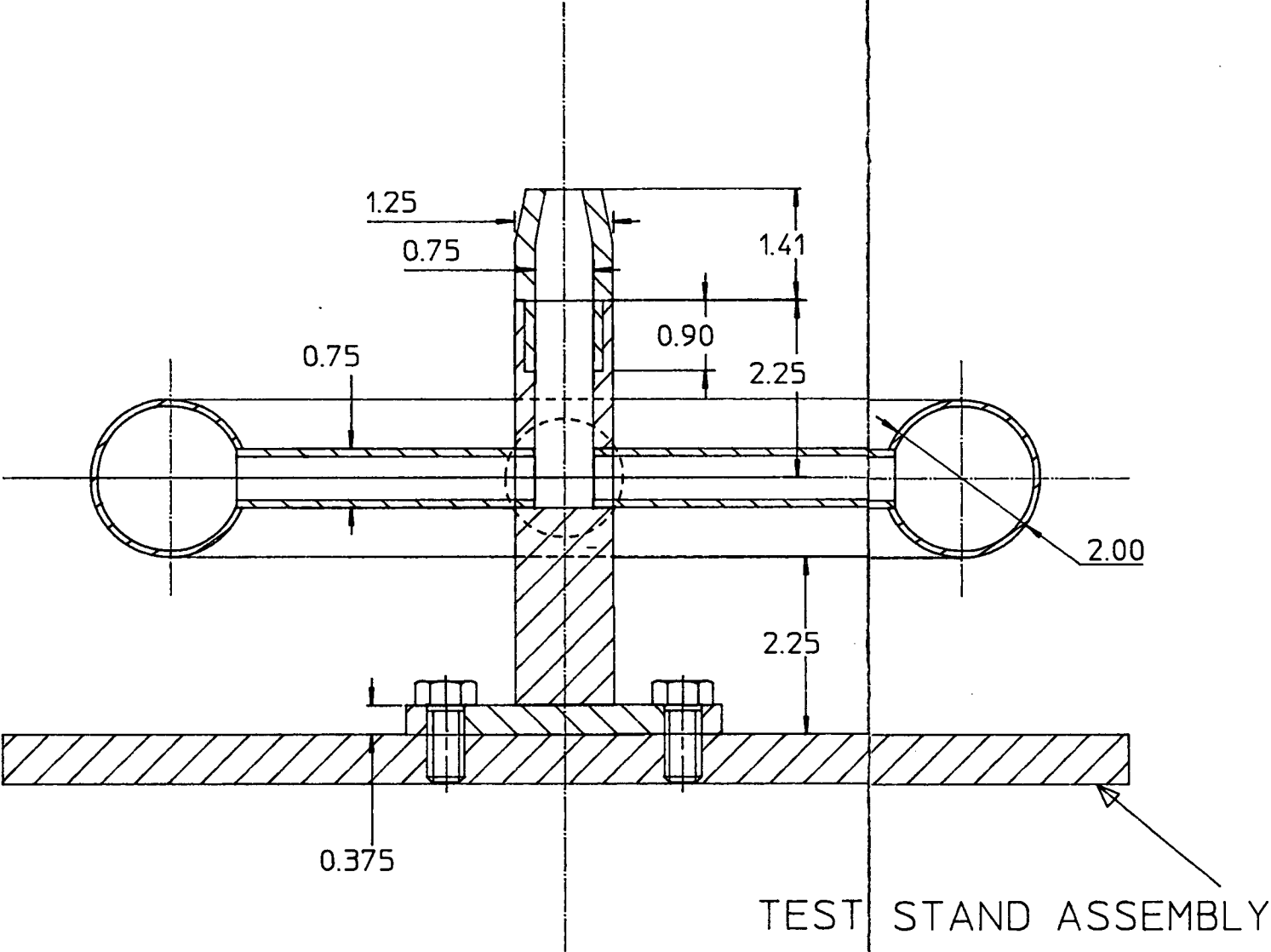


SIDE VIEW  
SECTION A-A

ITEM	QTY.	PART NO.	DESCRIPTION	SPECIFICATION
PARTS LIST				
MATERIAL: STAINLESS STEEL		CAL POLY MECHANICAL ENGINEERING DEPARTMENT PLENUM CHAMBER No.1		
SCALE: 1:2				
DIMENSIONS IN INCHES				
TOLERANCES: XX ± 0.01 XXX ± 0.002		PAGE: 2 OF 2		REV. NO.:
		DRAWN BY: G.C. MCINTOSH		DATE: 12 JANUARY 1990



ITEM	QTY.	PART NO.	DESCRIPTION	SPECIFICATION
PARTS LIST				
MATERIAL: STAINLESS STEEL		CAL POLY MECHANICAL ENGINEERING DEPARTMENT		
SCALE: 1:2		PLENUM CHAMBER No.2		
DIMENSIONS IN INCHES				
TOLERANCES: XX ± 0.01 .XXX ± 0.002		PAGE: 1 OF 2		REV. NO.:
		DRAWN BY: G.C. MCINTOSH		DATE: 12 JANUARY 1990



SIDE VIEW  
SECTION A-A

ITEM	QTY.	PART NO.	DESCRIPTION	SPECIFICATION
PARTS LIST				
MATERIAL: STAINLESS STEEL		CAL POLY MECHANICAL ENGINEERING DEPARTMENT		
SCALE: 1:2		PLENUM CHAMBER No.2		
DIMENSIONS IN INCHES				
TOLERANCES: .XX ± 0.01 .XXX ± 0.002		PAGE: 2 OF 2		REV. NO.:
		DRAWN BY: G.C. MCINTOSH		DATE: 12 JANUARY 1990

## **APPENDIX 3**

### **AIR SUPPLY SYSTEM**

#### **SECTION 1**

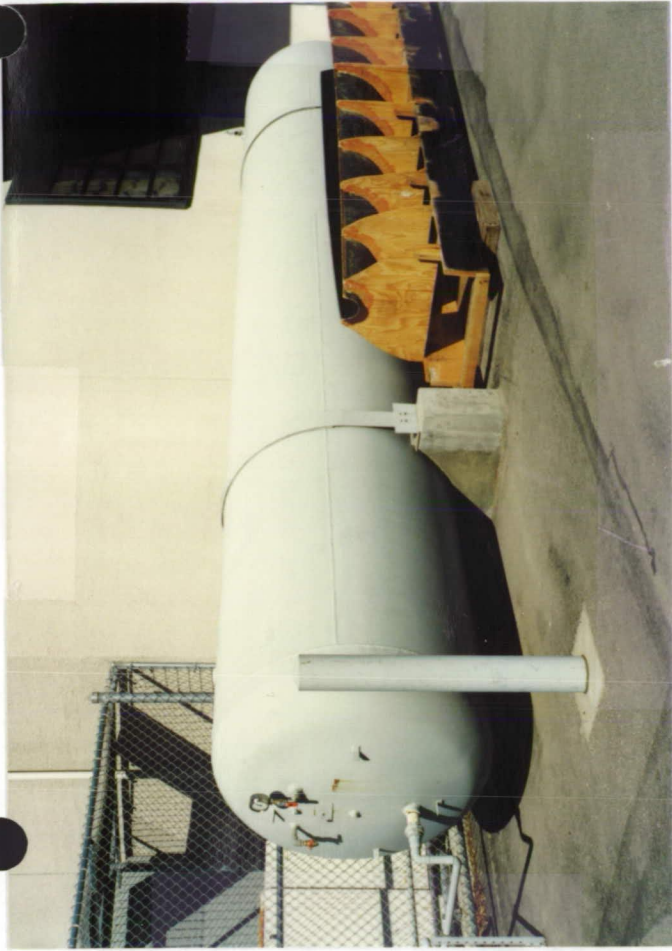
#### **SECTION 2**

#### **SECTION 3**

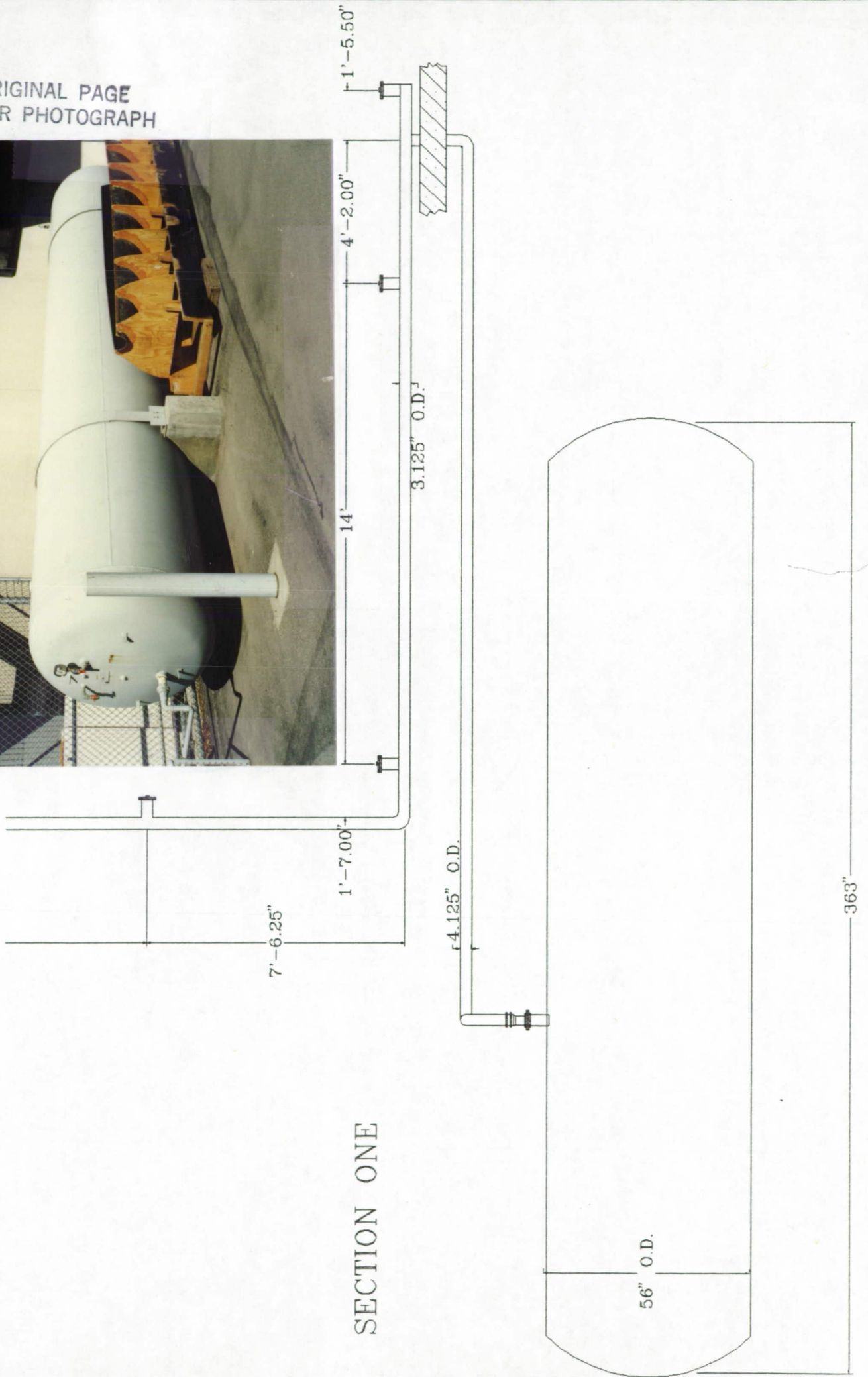
### **SAMPLE HEAD LOSS CALCULATIONS**



ORIGINAL PAGE  
COLOR PHOTOGRAPH



SECTION ONE



10.75"

8'-0.25"

7'-11.75"

8.00"

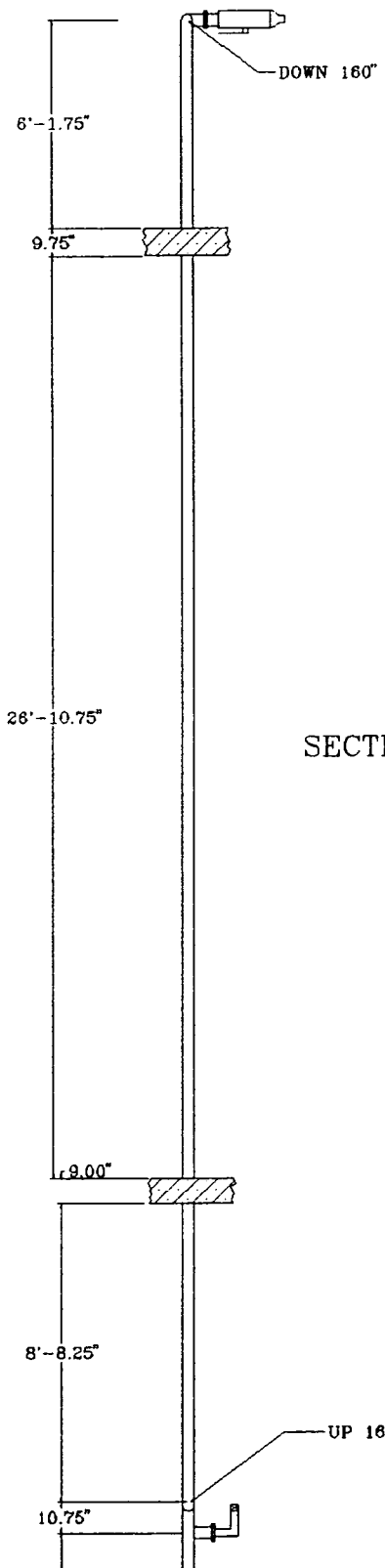
10'-2.00"

9'-6.00"

SECTION TWO

DOWN 160"

UP 160"



## Head Loss Calculations For Air

### ASSUMPTIONS

- \*smooth pipe
- \*constant temperature

INITIAL CONDITIONS				
Pressure Initial	Temp F	Mass Flow Rate		R
125 psi	530	2.5 lbm/s		640
Absolute Viscosity Mu				
1.019E-06 lbm/(in sec)				

### CALCULATIONS

Losses for section 'One' -----

Area	I.D. (in)	e/D	Length of Pipe (in)
7.402	3.07	5.700E-04	8.00

Density(lbm/cu.in.)	Velocity (in/s)	Reynolds Number Re
3.685E-04	916.469869	1.017E+06

Friction Factor	Pressure Change	New Pressure
1.745E-02	1.832E-02 psi	124.98 psi

Losses in the sudden expansion

Area 1	I.D. (in)	e/D	Length of Pipe (in)	Area 2
6.8118	2.9450	5.700E-04	8.00	11.9459

Density(lbm/cu.in.)	Velocity (in/s)	Reynolds Number Re
3.685E-04	996.065752	

Friction Factor	Pressure Change	New Pressure
	8.792E-02 psi	1.249E+02 psi

Losses in the Butterfly Valve

Area 1	I.D. (in)
11.946	3.9000

Density(lbm/cu.in.)	Velocity (in/s)
3.682E-04	568.375068

Pressure Change	New Pressure
0.1549 psi	124.7389 psi

Losses in the four-inch Dia length of Pipe

Area 1	I.D. (in)	e/D	Length of Pipe (in)	Bends
11.946	3.900	2.000E-05	340	3

Density(lbm/cu.in.)	Velocity (in/s)	Reynolds Number Re
3.677E-04	569.080779	8.009E+05

Friction Factor	Pressure Change	New Pressure
1.106E-02	0.1891 psi	124.5498 psi

Losses in the 3-inch Dia length of pipe

Area 1	I.D. (in)	e/D	Length of Pipe (in)	Bends
6.812	2.95	2.000E-05	308	1

Density(lbm/cu.in.)	Velocity (in/s)	Reynolds Number Re	Branches
3.672E-04	999.519864	1.061E+06	2

Friction Factor	Pressure Change	New Pressure
0.0107	0.6577 psi	123.8920 psi

Losses Through Section 'Two'

Area 1	I.D. (in)	e/D	Length of Pipe (in)	Bends
6.812	2.945	2.000E-05	1296	6

Density(lbm/cu.in.)	Velocity (in/s)	Reynolds Number Re	Branches
3.652E-04	1004.82614	1.061E+06	4

Friction Factor	Pressure Change	New Pressure
0.0107	2.7218 psi	121.1702 psi

Losses Through Section 'Three'

Area 1	I.D. (in)	e/D	Length of Pipe (in)	Bends
6.812	2.945	2.000E-05	613	2

Density(lbm/cu.in.)	Velocity (in/s)	Reynolds Number Re
3.572E-04	1027.39732	1.061E+06

Friction Factor	Pressure Change	New Pressure
0.0107	1.2037 psi	119.9665 psi

Total Pressure Drop
5.0335 psi